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Joaquín Bautista, Cristina Batalla, Rocío Alfaro, Sara Llovera, Jordi Fortuny

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DESIGN AND BALANCING OF ASSEMBLY LINES THAT MINIMIZE ERGONOMIC RISK

Joaquín Bautista[1], Cristina Batalla[1], Rocío Alfaro[1], Sara Llovera[1], Jordi Fortuny[1]

[1]Universitat Politècnica de Catalunya – BarcelonaTech

Abstract: In this paper, an assessment system of the ergonomic hazards existing in the workstations of an assembly line is provided. A mathematic model to solve the assembly line balancing problem is developed with the aim of minimizing the ergonomic risk that exists in an assembly line by taking into account the number of workstations and a set of temporal and spatial restrictions. This model has been applied, by means of a computational experiment, in a problem taken from a case study of Nissan's engine plant in Barcelona. The experiment measures the impact that the increase in the number of workstations causes on the improvement of the ergonomic quality of such workplaces and on the reduction of the ergonomic risk.

Keywords: Assembly line balancing; TSALBP; Ergonomics; Ergonomic Risk; Logistics; Manufacturing.

1. Introduction

Ergonomics is the scientific study of the relationship between man and his working environment, including tools, materials, methods of work and organization of his work. Applying Ergonomics to the workplace can reduce the likelihood of accidents and the potential for ill health at work. However, in many countries, Ergonomics just focuses on the prevention of Work-Related Musculoskeletal Disorders (WMSDs) because WMSDs constitute an important and expensive occupational problem, with rising costs of wage compensation and medical expenses, reduced productivity, and lower quality of life. The member countries of the Organization for Economic Co-operation and Development (OECD) put in place many preventive measures with the purpose that the design of workstations (in production lines in the automotive industry) results in optimal ergonomic working conditions for the operators. Even so, the jobs/tasks in a production line still entail a set of characteristics or factors (demands on the worker; Type of equipment; information; physical environment) that may lead to mental and physical health problems.

The manual handling (involving heavy loads or repetitive lifting) required to assemble parts in the engine lines or the awkward postures required to fix elements inside a vehicle in the clothing lines (Trim & Chassis), where there is plenty of labor intensive manual tasks, are two examples of actions that, when repeated many times each day, lead to accidents, injury and ill health.

In the automotive industry, and in other activities such as the building industry, different methods can be used to separately assess each one of the several ergonomic risk factors (postural loads, repetitive movements or weight lifting). Among the internationally renowned ergonomic evaluation tools, we can mention:

- The Rapid Upper Limb Assessment (RULA) method (McAtamney and Corlett, 1993), devoted to estimating the risks of work-related upper limb disorders
- The Rapid Entire Body Assessment (REBA) worksheet (Hignett and McAtamney, 2000), based on the same principles as RULA, is a better tool for the whole body because it includes static, dynamic, unstable and rapidly changing postures but, since it was developed to assess the postures of health care workers, it may be less useful for production line jobs.
- The Ovako Working posture Analysis System (OWAS). It was developed in a Finnish steel industry company to describe the workload in the overhauling of iron smelting ovens. OWAS identifies the most common work postures and the weight of the load handled (Karhu et al., 1977; Karhu et al., 1981).
- The revised NIOSH lifting equation for the design and evaluation of manual lifting tasks (Waters et al., 1993; Waters et al., 1998).
- The job Strain Index (SI) is a methodology that results in a numerical score, which is correlated with the risk of developing distal upper extremity disorders (Moore and Garg, 1995). This approach is analogous to the NIOSH lifting index.
- The Occupational Repetitive Actions (OCRA) methods (Colombini et al., 2002) for calculating a concise index of exposure to repetitive movements of the upper limbs.
- Guia técnica para la manipulacion manual de cargas del Instituto nacional de Seguridad e Higiene en el trabajo (GINSHT) –this is the technical guide on manual handling of loads created by the Spanish National Institute for Occupational Safety and Health (Ruiz, 2011).
- Ergo/IBV (IBV, 2007). Ergo / IBV is a software that allows evaluating ergonomic and psychosocial risks associated with the job. Is widely used in Spain and is present elsewhere.

However, ergonomic workstation design is not the only problem that designers of assembly/production lines have to deal with. Currently, in the automotive industry, the manufacturing lines must be able to handle different types of models. For example, the engine line can manufacture both diesel and gasoline engines for crossovers and SUVs (Sport Utility Vehicle), vans and mid-size commercial trucks, and each type may come in a variety of engine displacements (volume swept by all the pistons inside the cylinders in a single movement). Although they may look similar, differences between models can entail different processing times, different parts and components and, broadly speaking, different resources.

A company attempts to design its manufacturing systems in the most efficient way. Over the years, certain types of facilities have come to be recognized as the most appropriate for a given combination of production quantity and product variety. Efficient production of large quantities of standardized products, also known as mass production, usually requires a product layout, termed production line, which involves workstations arranged in sequence while the work units move through the sequence to complete the final product (Boysen et al., 2008). The design of the production line takes into account the above mentioned variety of products and the restrictions associated with the technology of the product, the characteristics of the manufacturing plant and the desired production capacity.

The context above can be related to the assembly-line balancing problem (ALBP). The ALBP is a classic problem whose main objective is to design and manage product-oriented facilities intended for repetitive (mass) production.

The ALBP is well established in the Operations Research literature. Since the pioneering work of Salvenson (1955), this problem has been widely addressed in the literature (Baybars, 1986) with many variants and extensions of the basic model. They can be found in recent taxonomies (Becker and Scholl, 2006; Battaïa and Dolgui, 2013).

Amongst the many variants, the ALBP, under the circumstances described in this paper, can be characterized by three different groups of elements: The first one (1) is a set of operations or tasks (J: $j = 1, \dots, |J|$), which can be associated with temporal attributes (i.e. the performance time of each task, t_j: $j = 1, \dots, |J|$), spatial requirements (necessary area for each task a_j: $j = 1, \dots, |J|$) and ergonomic stress levels (i.e. ergonomic risk of each task: R_j: $j = 1, \dots, |J|$); the second one (2) is a set of workstations (K: $k = 1, \dots, |K|$) with finite or infinite elements; and the third one (3) is a set of sequencing restrictions and precedence relationships between tasks, restrictions of incompatibility, and a series of constraints that affect the stations respecting their assignable time, their available area and their admissible risk. Eventually, the ALBP attempts to assign all the tasks to the workstations in a way that all the constraints and limitations are observed and the system achieves its maximum efficiency.

In the literature, the most frequently used attributes are the temporal ones (processing times). In these problems, the time that each station spends working per unit of product is limited by the cycle time *(c)*. The Time and Space Assembly Line Balancing Problem (TSALBP) (Bautista and Pereira, 2007; Chica et al., 2010) is another type of problem that appears when, besides the time constraints, the characteristics of the areas required by the materials and tools to execute the operations in the stations are limited too.

In addition, some metrics and restrictions on ergonomic risk can be included (Otto and Scholl, 2011) to prevent workers on the assembly line from being injured by monotonous and awkward postures throughout the workday due to poor workplace ergonomics.

Following the same line of work, that consists in adding new requirements to the ALBP, Bautista, Batalla and Alfaro (Bautista et al., 2012) propose an extension of the TSALBP by incorporating restrictions that set upper and lower bounds to the physical and psychological risk caused by the workload. Risk is evaluated through the processing times of the operations and through a system of risk categories that monitors the risk during the execution of the task. In a later paper, Bautista et al. (2013) analyze, by means of restrictions, the increase in the number of workstations, in order to keep the capacity of the line, when an upper bound is applied to the ergonomic risk.

On the basis of the work by Bautista et al. (2013), we present a Mixed Integer Lineal Programming (MILP) model to balance a production line (a mixed-model assembly line) in Nissan's engine plant in Barcelona. The objective of the model is to minimize the ergonomic risk in a set of scenarios that represent changes in the number of possible workstations. Demand must be satisfied and therefore the production capacity of the line has to be preserved. The model includes the possibility of a limit in the space taken up by the production system, which is measured through the length of the line.

2. Ergonomic risk

Authors realized that the different tasks performed by associates working on the engine line involved many ergonomic hazards, to which workers were exposed, arising from improper work methods and poorly designed workstations, tools, and equipment. The most common physical risk factors are: (1) postural loads, (2) repetitive motions and (3) manual handling of loads. The majority of ergonomic assessment systems tend to focus solely on one type of ergonomic hazard.

Our proposal integrates RULA, NIOSH and OCRA methods for evaluating the ergonomic hazard of any task or set of tasks, with regard to either a single risk factor or a set of factors. These methods divide the grand score into action levels that show the urgency about the need to change how a person is working as a function of the degree of injury risk. Since each method divides its actions levels in a different way, we have integrated them into a new scale with four levels which guide the corrective actions that should be applied to improve the jobs on the engine line from the point of view of Ergonomics (Table 1).

Table 1: Descriptor of the risk level and the corrective action proposed for each level

Risk level	Descriptor	Corrective action
L1	Acceptable	No action is required because the task shows very low potential for accidents, injury or ill health.
L2	Mild-to Moderate	Further assessment of the workplace is recommended. Changes in the near future to prevent an injury.
L3	High	Urgent analysis of the workplace, correction of ergonomic hazard and medical surveillance. Check periodically.
L4	Unacceptable	Immediate re-design of the workplace due to severe ergonomic hazard exposure.

Although in this research only physical aspects have been analyzed, it is possible to extend the model in order to include psychological risks. In consequence, in order to carry out the integration of different assessment tools, we put forward the following model:

(1) We consider a set of physical and/or psychical risk factors Φ ($\phi = 1, \dots, |\Phi|$).

(2) Given the task $j \in J$ ($j = 1, \dots, |J|$) and the risk factor $\phi \in \Phi$ ($\phi = 1, \dots, |\Phi|$), a risk category is associated with this task $\chi_{\phi,j}$, as a function of the risk factor.

(3) A quantitative value $R_{\phi,j}$ for the ergonomic risk of the task $j \in J$ due to the risk factor $\phi \in \Phi$ is computed: the processing time of the task, t_j is multiplied by the risk category $\chi_{\phi,j}$ and thus $R_{\phi,j} = t_j \cdot \chi_{\phi,j}$.

In this paper, the ergonomic risk is measured in ergo-seconds *(e-s)*. An ergo-second is the time unit, measured in seconds, used to assess the ergonomic risk of a task, with a processing time of 1 second at normal work pace, bearing a Level 1 risk category. Thus, this scale measures the time that workers spend doing a task (work pace) taking into account the level of the ergonomic risk they are exposed to.

(4) The aggregated ergonomic risk can be measured, for tasks and factors, by adding elemental ergonomic risks $R_{\phi,j}$ under the assumption that the linear superposition principle is met.

In our proposal, the risk category $\chi_{\phi,j}$ associated to an elemental task $j \in J$ and a risk factor $\phi \in \Phi$ adopts values that are included into four risk levels (Table 1): (L1) Acceptable, $1 \leq \chi_{\phi,j} < 2$; (L2) Mild-to-moderate, $2 \leq \chi_{\phi,j} < 3$; (L3) High, $3 \leq \chi_{\phi,j} < 4$; (L4) Unacceptable, $\chi_{\phi,j} \geq 4$.

3. Mathematical model

We propose a mono-objective mathematical model to solve an assembly/ manufacturing line balancing problem. To design the line, we take into consideration both temporal and spatial aspects (as in the TSALBP family) and, besides, ergonomic aspects.

The proposed model considers a known and fixed number of stations, a linear area available in each job that has been previously established and a constant and known production rate that is the reciprocal of the desired cycle time. The problem to solve consists in assigning a set of elementary tasks to a set of workstations in a way that the line's overall ergonomic risk is minimal. Moreover, in any feasible workstation-task assignment, the following conditions must be satisfied: (1) the precedence constraints that exist between the tasks have to be met, (2) for each workstation, the performance time, which equals the sum of the processing times of each task performed at the station, should not exceed the cycle time, and (3) at any station, the linear area required by the work load has to be less than or equal to the available area for that workstation. In this model, areas are measured by the proxy variable "linear area", which is measured in units of length because we assume that the working space on both sides of the assembly line, where the workers move about and where components are stored, has an homogeneous width along the line. And it is enough for a comfortable work. In consequence, only the length of the workstations has to be taken into account in the optimization process.

The following lines are devoted to defining the parameters and the variables of the $M - min\,\bar{R}(\Phi)$ model and to formulating the model itself.

Parameters

J	Set of elementary tasks $(j = 1, \dots, \lvert J \rvert)$.
K	Set of workstations of the line $(k = 1, \dots, \lvert K \rvert)$.
Φ	Set of physical and psychological risk factors $(\phi = 1, \dots, \lvert \Phi \rvert)$.
t_j	Processing time of the task j $(j = 1, \dots, \lvert J \rvert)$ at normal pace .
a_j	Linear area required by the elementary task j $(j = 1, \dots, \lvert J \rvert)$.
$\chi_{\phi,j}$	Category of task j $(j = 1, \dots, \lvert J \rvert)$ in regard to risk factor ϕ $(\phi = 1, \dots, \lvert \Phi \rvert)$.
$R_{\phi,j}$	Ergonomic risk of task j $(j = 1, \dots, \lvert J \rvert)$ due to factor ϕ $(\phi = 1, \dots, \lvert \Phi \rvert)$ that is computed as follows: $R_{\phi,j} = t_j \cdot \chi_{\phi,j}$.
P_j	List of tasks that immediately precede task j $(j = 1, \dots, \lvert J \rvert)$.
c	Cycle time. Maximum time allowed to any workstation k $(k = 1, \dots, \lvert K \rvert)$ to execute the work assigned to it.
m	Number of workstations. In this case, $m = \lvert K \rvert$.
A	Linear area given to a workstation k $(k = 1, \dots, \lvert K \rvert)$. It has to be able to shelter the tasks assigned to the station.

Variables

$x_{j,k}$	Binary variable which takes value 1 if the task j $(j = 1, \dots, \lvert J \rvert)$ is assigned to the workstation k $(k = 1, \dots, \lvert K \rvert)$ and value 0 otherwise.
S_k	Workload of station k $(k = 1, \dots, \lvert K \rvert)$. It is a list of tasks assigned to station $k \in K$
R_ϕ	Maximum ergonomic risk in regard to risk factor ϕ $(\phi = 1, \dots, \lvert \Phi \rvert)$ that is allowed to each workstation k $(k = 1, \dots, \lvert K \rvert)$ to perform all the tasks assigned to it S_k .
$\bar{R}(\Phi)$	Average ergonomic risk due to the set of factors Φ related to the production line.

Formulation $M - min\,\bar{R}(\Phi)$

$$min\,\bar{R}(\Phi) = \frac{1}{\lvert \Phi \rvert} \sum_{\phi=1}^{\lvert \Phi \rvert} R_\phi \tag{1.1}$$

Subject to:

$$\sum_{\forall k \in K} x_{j,k} = 1 \qquad (j = 1, \dots, \lvert J \rvert) \tag{1.2}$$

$$\sum_{\forall j \in J} t_j \cdot x_{j,k} \leq c \qquad (k = 1, \dots, |K|) \qquad (1.3)$$

$$\sum_{\forall j \in J} a_j \cdot x_{j,k} \leq A \qquad (k = 1, \dots, |K|) \qquad (1.4)$$

$$R_\phi - \sum_{\forall j \in J} R_{\phi,j} \cdot x_{j,k} \geq 0 \qquad (k = 1, \dots, |K|) \wedge (\phi = 1, \dots, |\Phi|) \qquad (1.5)$$

$$\sum_{\forall k \in K} k\left(x_{i,k} - x_{j,k}\right) \leq 0 \qquad \left(1 \leq i,j \leq |J| : i \in P_j\right) \qquad (1.6)$$

$$\sum_{\forall k \in K} k \cdot x_{j,k} \leq m \qquad (j = 1, \dots, |J|) \qquad (1.7)$$

$$\sum_{\forall j \in J} x_{j,k} \geq 1 \qquad (k = 1, \dots, |K|) \qquad (1.8)$$

$$x_{j,k} \in \{0,1\} \qquad (j = 1, \dots, |J|) \wedge (k = 1, \dots, |K|) \qquad (1.9)$$

In $M - min\,\bar{R}(\Phi)$, the objective function (1.1) expresses the minimization of the ergonomic risk of the line. The risk is measured as the average ergonomic risk due to a set of factors Φ. The set of constraints (1.2), one equation for each task, makes sure that each task is assigned to a station -and only one station- of the line. The set of constraints (1.3), with a constraint for every station, computes the processing time corresponding to the tasks assigned to each station. This value cannot be longer that the cycle time. The set of constraints (1.4), with also one constraint for every station, prevents that the linear area required by the workload of each station from being longer than the length of the linear area given to each station. The set of constraints (1.5) includes one constraint for each possible combination of workstation and risk factor. These expressions set limit, for each risk factor, to the ergonomic risk caused by the tasks assigned to a particular workstation. The ergonomic risk must be smaller than the value of the maximum ergonomic risk allowed for each factor in each workstation of the line. The set of constraints (1.6) contains one constraint for each precedence relationship between two tasks and it makes sure that the assignment of tasks to workstations is feasible because it satisfies the order in which these tasks must be executed, in accordance with the logical relationships between tasks (task sequences and dependencies). The set of constraints (1.7), one expression for each task, is intended to limit the maximum number of stations. The set of constraints (1.8), which contains one constraint for each station, compels each workstation to complete at least one task. Finally, the set of conditions (1.9), with one requirement for each allocation variable adds the specification that these variables are binary (they have to take on the value 0 or 1 because they represent whether a given task is assigned to a certain station or not).

4. Computational experience

The $M - min\,\bar{R}(\Phi)$ model was used in a computational experiment aimed at measuring the impact caused by an increase in the number of workstations on the reduction of ergonomic risk to which workers were exposed. The experiment used data from a real assembly line, which were collected from a case study in Nissan's engine plant in Barcelona (*NSIO:* Nissan Spanish Industrial Operations).

The engine line has to satisfy a daily global demand of 270 units. To achieve this daily schedule, the plant runs on two eight-hour shifts, although effective daily working time per shift is 6 hour and 45 minutes taking into account compulsory breaks and other stoppages. Thus, the resulting cycle time *(c)* is 180 s.

Since this is a mixed-model line, different kinds of engines are assembled on it. We take into consideration 9 kind of engines grouped in 3 families: p_1, p_2 and p_3 are engines for crossovers and SUVs; p_4 and p_5 are for vans; and p_6, p_7, p_8 and p_9 are intended for medium tonnage trucks. In this paper, a daily demand of 30 units for each type of engine is assumed.

The assembly of any type of engine (750 parts and 330 references) comprises 370 elementary tasks, including a rapid test. These elementary tasks are grouped in 140 operations which respect the precedence relations between tasks and the consistency in terms of tool usage and skills required to execute the tasks.

The formulation was solved with the CPLEX (v11.0) software, running on a Mac Pro computer with an Intel Xeon, 3.0 GHz CPU and 2 GB RAM memory under the Windows XP operating system. In all the executions, the CPU time was limited to 2 hours.

The experiment yielded 5 line configurations whose number of workstations was between 19 and 23 (both inclusive), regardless of the available space for the workstations. In the 5 cases, the objective was to minimize $\bar{R}(\Phi)$ - the ergonomic risk of the line for the set of risk factors Φ (Postural loads, Repetitive motions and manual handling of loads)-.

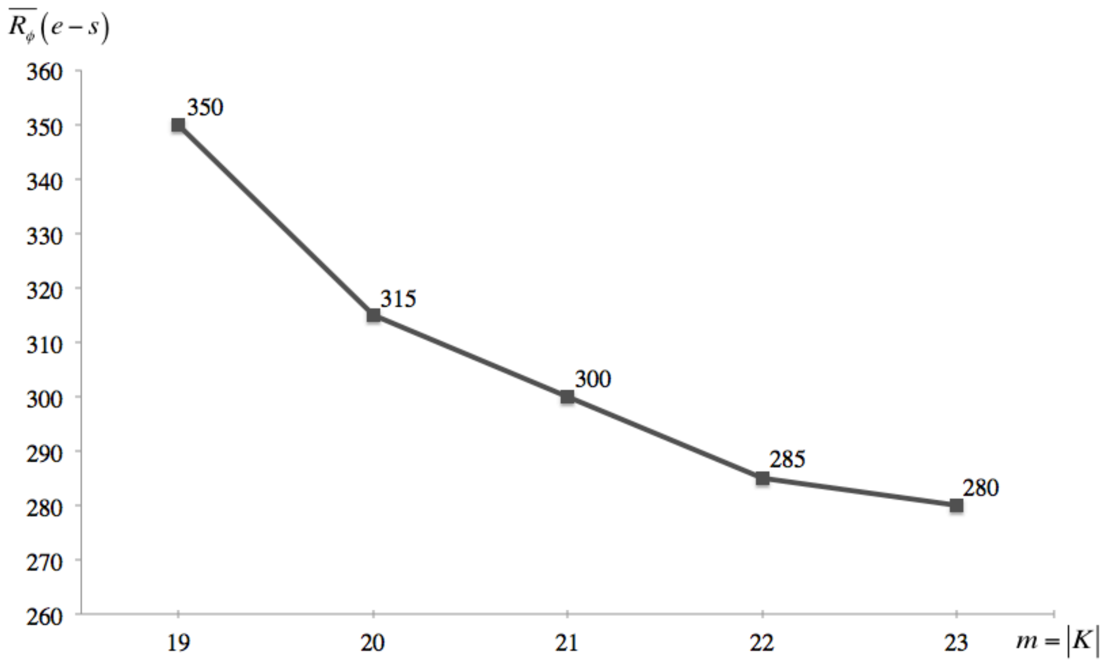
The temporal, spatial and ergonomic characteristics of the 140 assembly operations $j \in J$ for a production mix of 9 types of homogeneous engines (30 units by type) are shown in table A.1 (see Appendix). The same table shows the number of the station to which each operation has been assigned, in each one of the resulting five configurations of the line, with a number of workstations ranging from 19 to 23.

Next, figure 1 shows how an increase in the number of workstations entails a reduction of the ergonomic risk of the line, which is the average value of the different maximum ergonomic risks, in regard to each risk factor, that is allowed to the workstations.

When the line is made up of 19 workstations, the maximum ergonomic risk score that is allowed to any station is 350 *e-s (ergo-seconds)*. This represents a risk category value of 1.94 (which falls within L1 level but very close to L2 level) and therefore although the value of this category corresponds to an acceptable level, it is advisable to investigate how to improve the operation and to correct its risk. This preventive measure takes into account that a variation of the performance time, for example due to a change in the production mix, might result in a change in the value of the risk category and the associated risk level.

Figure 1 shows that the limit risk of the assembly line decreases as the number of workstations increases, and thus the limit risk is 315 *e-s* (a risk category value of 1.75) with 20 stations; 300 *e-s* (risk category is 1.66) with 21 stations; 285 *e-s* (1.58) with 22 stations and 280 *e-s* (1.56) with 23 stations.

Figure 1: Limit value of the ergonomic risk $\left(\overline{R}_{\phi}\right)$ of the line depending on the number of stations $(m = |K|)$.



Finally, table 2 shows the temporal, spatial and ergonomic characteristics of the workstations for the five configurations of the line with a maximum number of stations included between 19 and 23.

In table 2, we see that, as the number of workstations increases, the average and the minimum values of the stations' performance time decrease. Namely, a layout with 19 stations has a minimum performance time of 115 s (stations No. 6 and No. 7) while a line with 23 stations has a minimum station time of 75 s. (station No. 15). In consequence, the workload is not well balanced and while some workstations bear operations that lead to saturation, other stations remain idle during an important fraction of the cycle (compare station No. 15 and station No. 23). If current cycle time has to be preserved, job rotation may compensate the lack of balance by temporarily reducing the strain that some operations put on the workers. Otherwise, the line should be balanced again with a shorter cycle time.

With respect to the linear area required by the stations, it was not restricted in this experiment although the model may include constraints that set limits to the areas. The maximum values are over 6 meters in all configurations, reaching 8 m (station 1) in the layout with 22 stations. In consequence, it would be advisable to re-balance the line, including the spatial constraints, in order to see how this approach affects the ergonomic risk.

Table 2: Values of processing time $t(S_k)$ in seconds, linear area $a(S_k)$ in meters and ergonomic risk $R_\phi(S_k)$ in ergo-seconds for each station $S_k: k \in K$, for 5 configurations of the line $m = 19, \dots, 23$.

	$m=19$			$m=20$			$m=21$			$m=22$			$m=23$		
k	$t(S_k)$	$a(S_k)$	$R_\phi(S_k)$	$t(S_k)$	$a(S_k)$	$R_\phi(S_k)$	$t(S_k)$	$a(S_k)$	$R_\phi(S_k)$	$t(S_k)$	$a(S_k)$	$R_\phi(S_k)$	$t(S_k)$	$a(S_k)$	$R_\phi(S_k)$
1	180	7.5	265	180	6	300	180	6.5	285	171	8	267	173	7.5	271
2	176	5	332	173	4.5	311	161	5	282	180	3	260	160	2.5	280
3	179	5	298	180	6	280	175	4	290	142	4.5	284	168	5.5	276
4	175	5	320	177	6.5	299	174	6.5	298	172	5.5	284	169	6	278
5	125	7.5	350	105	6.5	315	105	5.5	290	105	4	275	110	3.5	280
6	115	1.5	345	105	1.5	315	100	2.5	300	100	3.5	285	90	3.5	270
7	115	1.5	345	105	2	315	100	2	300	95	4	285	80	3.5	240
8	120	1.5	340	105	0	315	100	1	300	95	1.5	285	90	1	270
9	170	4.5	340	140	3.5	315	110	2	290	95	0	285	90	1	270
10	175	5.5	350	155	4.5	310	150	4	300	130	3	285	115	2	280
11	175	6.5	350	155	6	310	150	5	300	140	4	280	130	3.5	260
12	130	2.75	335	130	3.75	315	150	5.5	300	135	4.5	270	130	4.5	260
13	140	1.5	340	120	2.5	315	110	2.25	285	140	5.5	280	140	5.5	280
14	155	3	350	130	1	290	95	1.5	285	120	2.25	285	110	2.25	275
15	170	2	340	155	2.5	315	150	2	300	95	2.5	285	75	1.5	225
16	180	4	345	170	3	315	145	3	295	125	1	285	120	0.5	270
17	170	5	285	175	4.5	315	140	1.5	280	140	3	285	130	2.5	265
18	160	4.25	265	180	4.5	315	175	4	295	140	1.5	280	140	3	280
19	180	2	250	170	3.75	295	165	4	295	140	3	285	160	2.5	280
20				180	3	285	175	4.75	290	170	4.5	280	150	3.5	275
21							180	3	285	180	4.25	280	165	5	280
22										180	2.5	255	115	2.75	225
23													180	2.5	255
Aver	157.4	4.0	323.4	149.5	3.8	307.3	142.4	3.6	292.6	135.9	3.4	279.3	130.0	3.3	267.2
Min	115	1.5	250	105	0	280	95	1	280	95	0	255	75	0.5	225
Max	180	7.5	350	180	6.5	315	180	6.5	300	180	8	285	180	7.5	280

Concerning the ergonomic risk, the best configuration is a line with 23 stations, which yields an average value of 267.2 *e-s* (with values ranging from a minimum of 225 *e-s* to a maximum of 280 *e-s*). However, among the 5 configurations that were studied, the layout with the least dispersion (the one with most uniformity from the point of view of ergonomic risk) is the line with 21 stations, with a range (difference between minimum and maximum values) of 20 *e-s* and a standard deviation of 6.9 *e-s*.

Finally, with regard to the risk category, the 5 configurations show values below 2 (their maximum values fall between 1.6 and 1.9 and their average values result between 1.5 for the line with 23 stations and 1.8 for the line with 19 stations). In summary, it may be concluded that the resulting five production lines have low risk levels, ranging from acceptable to practically moderate.

5. Conclusions

Ergonomic design of the workspaces is fundamental in any production system. But when designing workstations in a production line, besides ensuring employees' health and wellbeing (measured as an acceptable level of ergonomic risk), it is necessary to consider several requirements that affect the number of workstations (m), the cycle time (c) to complete the tasks and the available area in each workplace (A).

In this paper, taking as a starting point the TSALBP family, we propose a model to balance assembly/production lines in order to minimize the ergonomic risk while satisfying a set of constraints, which take into consideration spatial and temporal aspects.

After analyzing data from a case study in Nissan's engine plant in Barcelona, we would suggest the managers to create new workstations as a measure designed to reduce the ergonomic risk of the assembly line without changing its production capacity.

In future works, we will measure the impact caused by the limitation of the available space in the stations; we will establish how to redistribute tasks between stations of a given line configuration in the short to medium term; and we will compare the savings in costs of healthcare which derive from risk reduction (because less injuries should occur) with the increased manufacturing costs due to the creation of new jobs.

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APPENDIX

Table A.1: Performance time at normal pace (t_j) in seconds (s), required area (a_j) in meters (m), risk category $(\chi_{\phi,j})$ is dimensionless and ergonomic risk $(R_{\phi,j})$ in ergo-seconds $(e-s)$ associated to each task $j \in J$. Columns $k_{(m=19,\dots,23)}$ show the number of the station where each task is performed, in a line with $m = 19, \dots, 23$ stations.

Data					*k Into line of m stations*				
$j \in J$	$t_j(s)$	$a_j(m)$	$\chi_{\phi,j}$	$R_{\phi,j}(e-s)$	$m=19$	$m=20$	$m=21$	$m=22$	$m=23$
1	60.00	3	1	60	1	1	1	1	1
2	75.00	2	2	150	11	18	20	13	6
3	20.00	0.5	1	20	2	2	2	2	2
4	60.00	1	1	60	3	3	3	3	2
5	20.00	0.5	1	20	1	2	2	2	2
6	60.00	1.5	1	60	4	4	4	4	4
7	45.00	1	2	90	4	1	1	1	4
8	10.00	0.5	2	20	2	4	1	3	5
9	20.00	0.5	2	40	1	1	1	1	1
10	30.00	0.5	2	60	1	1	1	2	1
11	15.00	0.5	2	30	1	2	2	1	1
12	15.00	0.5	2	30	16	10	5	1	7
13	15.00	1	1	15	1	1	1	1	1
14	10.00	0.5	2	20	1	1	2	1	1
15	8.00	1	2	16	2	3	2	3	1
16	8.00	0.5	2	16	2	3	2	3	1
17	80.00	1	2	160	2	2	2	2	2
18	40.00	0.5	2	80	2	2	3	3	3
19	5.00	0.5	2	10	1	3	3	3	3
20	5.00	0.5	2	10	2	3	2	2	3
21	5.00	0.5	2	10	1	3	3	2	1
22	7.00	0.5	2	14	3	3	4	4	3
23	7.00	0.5	2	14	3	3	4	4	3
24	30.00	0.5	2	60	3	3	3	3	3
25	30.00	0.5	2	60	3	3	3	4	3
26	5.00	0.5	2	10	3	3	3	3	3
27	5.00	0.5	2	10	2	3	3	3	3
28	30.00	1	2	60	3	4	4	4	4
29	10.00	0.5	2	20	3	4	4	4	4
30	15.00	1	2	30	4	4	4	4	4
31	10.00	0	2	20	4	4	4	4	5
32	15.00	0.5	2	30	4	4	4	5	5
33	30.00	1	3	90	4	5	5	5	5
34	10.00	0.5	3	30	5	5	5	5	6
35	5.00	0.5	3	15	5	4	5	5	5
36	25.00	1	2	50	5	4	4	5	5

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Data					*k Into line of m stations*				
$j \in J$	$t_j(s)$	$a_j(m)$	$\chi_{\phi,j}$	$R_{\phi,j}(e-s)$	$m=19$	$m=20$	$m=21$	$m=22$	$m=23$
37	15.00	0	3	45	5	5	5	5	5
38	5.00	0.5	3	15	5	5	5	6	6
39	5.00	0.5	3	15	5	5	5	6	6
40	5.00	0.5	3	15	5	5	5	5	6
41	60.00	0.5	3	180	6	6	6	6	7
42	15.00	1.5	3	45	5	5	6	7	6
43	15.00	1.5	3	45	5	5	5	6	7
44	25.00	0.5	3	75	6	6	7	7	8
45	25.00	0.5	3	75	6	7	6	7	8
46	5.00	0.5	3	15	7	7	7	7	8
47	35.00	0.5	3	105	7	7	7	8	8
48	35.00	0.5	3	105	7	7	7	8	9
49	5.00	0.5	3	15	5	5	8	7	9
50	15.00	0.5	3	45	8	9	8	9	10
51	25.00	0	3	75	8	8	9	9	10
52	30.00	0	3	90	8	8	8	9	9
53	15.00	0	3	45	7	8	8	9	10
54	15.00	0	3	45	7	8	9	10	10
55	20.00	0	3	60	8	8	9	8	10
56	10.00	0	3	30	7	9	8	9	11
57	10.00	0.5	3	30	8	9	9	10	11
58	20.00	0.5	2	40	8	9	10	10	11
59	5.00	0	3	15	6	7	8	6	7
60	20.00	0.5	3	60	5	6	8	7	9
61	45.00	1	2	90	9	9	10	10	11
62	30.00	0.5	2	60	9	9	10	11	11
63	30.00	0.5	2	60	9	10	9	10	12
64	10.00	0.5	2	20	9	9	9	10	11
65	5.00	0	2	10	10	10	11	11	12
66	10.00	0.5	2	20	9	10	10	11	12
67	15.00	0.5	2	30	9	10	10	11	12
68	60.00	1.5	2	120	10	10	11	11	12
69	10.00	0.5	2	20	10	10	11	11	13
70	30.00	1	2	60	9	11	10	12	13
71	10.00	0.5	2	20	10	10	11	11	12
72	10.00	0.5	2	20	10	11	11	12	13
73	40.00	1.5	2	80	10	11	11	12	13
74	25.00	0.5	2	50	10	11	12	12	13
75	10.00	0.5	2	20	11	11	12	12	14
76	10.00	1	2	20	11	11	12	12	13
77	15.00	0.5	2	30	11	11	12	12	14
78	15.00	0.5	2	30	11	12	12	13	14
79	15.00	0.5	2	30	10	11	12	13	14
80	10.00	0.5	2	20	11	12	12	13	14

Continued on next page.

Data					*k Into line of m stations*				
$j \in J$	$t_j(s)$	$a_j(m)$	$\chi_{\phi,j}$	$R_{\phi,j}(e-s)$	$m=19$	$m=20$	$m=21$	$m=22$	$m=23$
81	10.00	1	2	20	11	12	12	13	14
82	10.00	0	2	20	11	12	12	13	14
83	20.00	0.5	2	40	12	12	13	14	14
84	10.00	0	2	20	12	12	13	14	14
85	20.00	0.5	3	60	12	12	13	15	15
86	25.00	0.5	2	50	12	13	12	14	15
87	20.00	0.5	2	40	11	13	13	14	15
88	15.00	0.25	3	45	12	12	13	14	14
89	20.00	0.5	3	60	12	12	14	15	15
90	30.00	0.5	3	90	13	13	13	14	16
91	20.00	0.5	3	60	12	13	14	15	15
92	25.00	0.5	3	75	13	13	14	16	16
93	10.00	0.5	3	30	16	20	21	22	16
94	5.00	0.5	3	15	13	14	19	15	16
95	20.00	0.5	3	60	19	20	21	22	16
96	10.00	0.5	3	30	19	20	21	22	23
97	5.00	0.5	3	15	19	20	21	22	23
98	80.00	0	2	160	13	14	15	16	17
99	30.00	0	3	90	14	14	14	15	17
100	10.00	0.5	2	20	14	14	15	16	17
101	10.00	0.5	2	20	14	14	15	16	18
102	20.00	0.5	2	40	14	15	15	17	18
103	30.00	0.5	2	60	14	15	16	17	18
104	5.00	0	3	15	14	15	16	17	18
105	30.00	0.5	2	60	15	17	16	18	20
106	25.00	0.5	2	50	14	17	15	18	18
107	5.00	0	3	15	14	15	16	17	19
108	5.00	0	2	10	14	15	16	17	18
109	5.00	0.5	2	10	14	15	16	17	18
110	5.00	0	2	10	15	15	16	18	23
111	10.00	0	2	20	14	15	16	17	18
112	10.00	0	2	20	15	15	16	18	18
113	15.00	0.5	2	30	15	15	16	17	18
114	20.00	0	2	40	15	15	17	17	19
115	20.00	0	2	40	15	15	16	17	19
116	45.00	1	2	90	15	16	17	18	19
117	20.00	0.5	2	40	16	16	17	19	19
118	25.00	0	2	50	15	16	17	18	19
119	25.00	0	2	50	16	17	18	19	20
120	20.00	0.5	2	40	16	17	18	19	20
121	45.00	1.5	2	90	17	17	18	19	21
122	15.00	0.5	1	15	17	17	18	19	21
123	10.00	0.5	1	10	17	17	18	20	21
124	10.00	0	1	10	17	18	18	20	21

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Data					*k Into line of m stations*				
$j \in J$	$t_j(s)$	$a_j(m)$	$\chi_{\phi,j}$	$R_{\phi,j}(e-s)$	$m = 19$	$m = 20$	$m = 21$	$m = 22$	$m = 23$
125	20.00	1	1	20	17	18	18	20	21
126	30.00	0.5	2	60	17	18	18	20	21
127	10.00	0.5	2	20	17	18	19	20	21
128	25.00	0.5	2	50	16	19	19	19	21
129	30.00	0.5	2	60	17	19	20	21	22
130	30.00	0.75	2	60	18	19	20	21	22
131	40.00	0.5	2	80	16	16	17	20	20
132	25.00	1	1	25	16	16	19	20	20
133	25.00	0.5	1	25	19	19	20	21	23
134	20.00	0.5	1	20	18	16	19	20	20
135	15.00	0.5	1	15	18	18	19	20	22
136	20.00	0.5	1	20	18	18	19	21	22
137	30.00	0.5	2	60	18	19	19	21	22
138	30.00	0.5	2	60	18	19	19	21	22
139	15.00	1	2	30	18	20	21	22	23
140	120.00	0	1	120	19	20	21	22	23